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An Evaluation of a High Temperature Blackbody As A Working Standard of Spectral Radiance

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SUMMARY

For those interested in measuring the spectral radiance of high intensity arcs, especially in the ultraviolet region, the 3000°C blackbody has several advantages over the conventional tungsten ribbon filament standard of spectral radiance. At a wavelength of 250 nanometers, it is between two and three orders of magnitude more intense and could have 30% to 40% less uncertainty in its spectral radiance. Moreover, by using the blackbody, measurements could be extended to wavelengths shorter than 250 nanometers. On the other hand, the intensity advantage of the blackbody can be nearly eliminated by operating and calibrating a tungsten standard-type lamp well over its rated current. Tests have shown that the stability of these lamps operated at 45 amps and 50 amps is suitable for calibration purposes.

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AN EVALUATION OF THE HIGH TEMPERATURE BLACKBODY AS A WORKING STANDARD OF SPECTRAL RADIANCE

by

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INTRODUCTION

In recent years many groups investigating the spectroradiometric properties of various high intensity light sources have felt the need for a spectral radiance standard which would be much more intense than the present tungsten ribbon filament lamp and would also permit greater accuracy. In response to this need, several manufacturers have offered to construct blackbodies, which would operate at 3000°C. The following analysis was performed to evaluate the advantages of the high temperature blackbody, and to provide some additional information bearing upon the use of such equipment in a research program.

DISCUSSION

To determine the increase in spectral radiance which may be achieved by using a blackbody, the spectral radiance of a blackbody operating at 3000°C has been computed for several wavelengths from Planck's radiation law. This data is shown in Table I along with the reported values for a tungsten ribbon filament lamp (General Electric Co. type G.E. 30A/T24/7), which was calibrated in terms of spectral radiance at the national Bureau of Standards. Also shown are the ratios of the blackbody values to the tungsten lamp values.

Table I

Wavelength (in nm)	Spectral Radiance 3000°C Blackbody	(in μwatt/ster-nm-mm^2) EU-171 @35 amps	Blackbody / EU-171
250	2.84	.00467	608
300	21.5	.106	203
350	80.4	.751	107
400	198.	2.93	67.6
450	362.	7.79	47.8
500	580.	16.5	35.2
600	1015.	42.6	23.8

It may be observed from the data in Table I that the 3000°C blackbody provides an increase in spectral radiance of between one and two orders of magnitude in the visible portion of the spectrum, and from two to three orders of magnitude in the ultraviolet region. Some idea of the significance of this increase may be derived by comparing the blackbody values to published data for some relatively low-powered compact arc lamps. This data is shown in Table II.

Table II

Wavelength (in nm)	Spectral Radiance (in µwatt/ster-nm-mm^2)			Ratio	
	Hanovia HgXe[1] @2800 Watts	Osram Xe[2] @1600 Watts	Blackbody @3000°C	$\frac{\text{HgXe}}{\text{Blackbody}}$	$\frac{\text{Xe}}{\text{Blackbody}}$
250	2,000	4,300	2.84	700	1500
300	50,000	5,500	21.5	2300	260
350	20,000	7,500	80.4	250	93
400	70,000	9,600	198.	350	48
450	4,000	11,500	372.	11	31
500	3,000	9,100	580.	5.2	16

Clearly the use of the blackbody standard will not eliminate the need for other scaling techniques. As may be seen in Table II, the spectral radiance of even the low powered arcs considered is still as much as three orders of magnitude greater than that of the blackbody. At the very best, the blackbody can go only about half way towards matching the intensity of the arcs.

Moreover, it appears to be possible to do nearly this well with the existing tungsten ribbon filament lamp. The spectral radiance of these lamps varies widely from one lamp to the next in the ultraviolet region. Table III shows a comparison of the 3000°C blackbody and a working standard, which was calibrated by comparing it with a lamp calibrated by NBS. Note that for the same current, this lamp is more than twice as intense as the lamp considered on Table I.

Table III

Wavelength	Spectral Radiance (in μwatt/ster-nm-mm²) 3000°C Blackbody	Lamp J @35 amps	N_λ(Blackbody) / $N_{\lambda(J)}$
250	2.84	.0120	237
300	21.5	.239	90.0
350	80.4	1.52	52.9
400	198.	5.50	36.0
450	372.	13.4	27.8
500	580.	27.0	21.5
600	1015.	63.7	15.9

A much greater potential for increased intensity exists if the current may be increased. Table IV shows for several wavelengths the spectral radiance of a lamp of this type as a function of current. The values given are relative to the spectral radiance of the same lamp at 35 amperes.

Table IV

Current	Relative Spectral Radiance of Tungsten Ribbon Filament Lamp			
(in amperes)	λ= 250 nm	λ= 300 nm	λ= 400 nm	λ= 500 nm
35.0	1.0	1.0	1.0	1.0
37.5	2.7	2.2	1.7	1.6
40.0	7.1	4.9	2.9	2.7
42.5	15.	9.2	5.2	3.9
45.0	31.	17.	10.	6.1
47.5	57.	27.	15.	8.9
50.0	100.	46.	21.	14.

On the assumption that the spectral radiance of lamp J would show a similar increase with current, the factors given in Table IV have been multiplied by the absolute values for the spectral radiance at 35 amperes. These results have been compared with the spectral radiances of a 3000°C blackbody. In Table V, the spectral radiance of a 3000°C blackbody is shown relative to the spectral radiance of lamp J at several currents.

Table V

Wavelength (in nm)	Spectral Radiance of 3000°C Blackbody Relative to Lamp J			
	J @35 amps	J @40 amps	J @45 amps	J @50 amps
250	237.0	33.0	7.6	2.4
300	90.0	18.0	5.3	2.0
400	36.0	12.0	3.6	1.7
500	21.5	8.0	3.5	1.5

Note in Table V that with lamp J at only 40 amperes, much of the intensity advantage of the blackbody is already gone. At 250 nm the ratio between the two sources has already been reduced by a factor of seven. At 300 nm, little more than an order of magnitude separates the two sources. With lamp J operating at 45 amperes, the 3000°C blackbody is never as much as one order of magnitude more intense.

There appear to be no serious problems involved in calibrating and using lamps at these higher currents, but the question naturally arises concerning the calibration lifetime. This should be presumed to be relatively brief in the absence of good experimental data. However, some indication might be derived from brief experience with two lamps. One of these lamps was operated at 50 amperes for 42 hours before burning out. The relative spectral radiance of this lamp at 250 nm was observed for the last 12 hours. This data is presented in figure I. The discontinuity in the curve at an elapsed time of 6 hours is believed to be due to an error related to the warm-up of the lamp and power supply. A similar rise in the curve is noted for the previous day.

The other lamp was operated at 45 amperes for nearly 29 hours. The relative spectral radiance at 250 nm is shown in figure II as a function of time. A straight line has been fitted to the data and the run test for randomness applied. According to this test, the data are distributed about the line randomly, and therefore we need not suspect a non-linear curve. The slope of this line indicates that the observed rate of change of spectral radiance at 45 amperes was less than 0.03% per hours.

Though limited, this data clearly admits the possibility that a standard-type tungsten lamp may be sufficiently stable to calibrate and use in the measurement of the spectral distribution of an intense arc.

In summary, it may be stated that while the 3000°C blackbody offers a significant increase in spectral radiance at 250 nm over the tungsten standard lamp operated at 35 amperes, it is possible to calibrate and use these tungsten lamps at currents high enough so that the blackbody offers no significant advantage in spectral radiance.

To begin the analysis of the accuracy which might be achieved with the high temperature blackbody, it is appropriate to first consider the emissivity of the cavity. This is determined by the geometry of the cavity, the degree of uniformity of wall temperature, the reflectivity of the cavity walls, and the nature of this reflectivity, whether diffuse or specular[(3)]. If the optical properties of the cavity material are known, a cavity may be designed which will have a theoretical emissivity approaching unity.

Unfortunately at 3000°C the spectral emittance of the cavity material in the ultraviolet region is not known. A recent search of the literature turned up no information as to the spectral emissivity of any refractory material at 250 nanometers and 3000°C[(4-13)]. Moreover such information as was available showed considerable variation from one investigator to the next.

For example, Kibler et al.[(4)] showed that the spectral emissivity of pyrolytic graphite decreased with increasing temperature from 1611° to 2735°K, and was less than .1 for wavelengths shorter than 500 nm and temperatures above 1611°K.

The National Carbon Company[5], however, demonstrated that the emissivity of pyrolytic graphite is constant with temperature over the range of 500° to $1800^{\circ}K$ and is about .7 to .8 at 550 nm. The emissivity of spectroscopic graphite was shown to be constant with temperature to about $2400^{\circ}K$.

It seems evident that in the absence of a considerable body of new measurements the spectral emissivity of blackbody cavity materials at high temperatures and short wavelengths will be quite uncertain. Yet this fact alone need not preclude the construction of a useful blackbody. Conservative design based upon the recognition that the spectral emissivity may be as low as 0.1 should in theory permit the achievement of a cavity emissivity of .99 or better. A reasonable approach might be to design very conservatively for a cavity emissivity of at least .995 and then to accept a minimum uncertainty of ±0.5%. If such a design proved impractical, trade-offs would be required which could not help but lessen the value of this equipment.

The high temperature blackbody will probably require a window to close its aperture. A window will decrease power requirements and improve temperature stability by reducing convective cooling of the cavity. It will also provide the means for preventing oxygen from entering and combining with the hot wall material. This should extend the lifetime of the cavity.

There are two ways, however, in which a window will introduce error. The uncertainty in the transmission of the window at the pyrometer wavelength will make the cavity temperature uncertain, and uncertainty in the transmission of the window at all wavelengths will provide an uncertain degree of attenuation of the blackbody radiation.

When a window is used, the true temperature is given by

$$T_T = T_A \left[1 + \frac{T_A \lambda}{C_2} \ln R\right]^{-1} \qquad (1)$$

(See Appendix A for derivation)

where T_T = true temperature

T_A = apparent temperature or pyrometer reading

C_2 = Second radiation constant

λ = Effective wavelength of the pyrometer

and R = Window transmission at λ.

If this expression is differentiated with respect to R, then

$$\frac{dT_T}{dR} = -\frac{T_A^{\,2}\lambda}{R} \left[1 + \frac{T_A \lambda}{C_2} \ln R\right]^{-2}. \qquad (2)$$

The negative sign indicates the negative slope of equation (1), and is of no concern here. The approximation $\left[1 + \frac{T_A \lambda}{C_2} \ln R\right]^{-2} \approx 1$ may be made for present purposes and equation (2) becomes

$$\frac{dT_T}{dR} = -\frac{T_A^{\,2}\lambda}{C_2 R}. \qquad (3)$$

Let this now be written as

$$\Delta T_T = \frac{T_A^2 \lambda}{C_2 R} \Delta R \qquad (4)$$

where ΔT_T = the uncertainty of T_T in degrees Kelvin

ΔR = the uncertainty of the window transmission and T_A, λ, C_2, and R are as before.

If the following values are assumed,

λ = 650 nm (the effective wavelength of the radiation pyrometer)

C_2 = 1.4380 cm°K

and R = .95,

then the temperature error due to uncertainty in the transmission of the window may be calculated. Table VI shows the temperature errors resulting from several values of transmission uncertainty.

Table VI

T_A (in °K)	ΔT (in °K)		
	ΔR = .01	ΔR = .005	ΔR = .001
3273	5.1	2.6	0.51
3073	4.5	2.2	0.45

Temperature error may be related to error in spectral radiance by the following expression (See Appendix B for derivation):

$$\frac{\Delta N_\lambda}{N_\lambda} = \frac{C_2}{\lambda T^2} \Delta T, \qquad (5)$$

where ΔN_λ is the uncertainty in spectral radiance

ΔT is the uncertainty in temperature

λ is the wavelength of interest

T is the true temperature

and C_2 is the second radiation constant.

If the following values are assumed,

λ = 250 nm

C_2 = 1.4380 cm-°K

then the uncertainty in spectral radiance introduced by uncertainty in the blackbody cavity temperature may be calculated.

Table VII shows the uncertainties in spectral radiance at λ = 250 nm resulting for various uncertainties in window transmission at the pyrometer's effective wavelength.

Table VII

T (in °K)	$\frac{\Delta N_\lambda}{N_\lambda}$ x 100 (at λ = 250nm)		
	ΔR = .01	ΔR = .005	ΔR = .001
3273	2.7%	1.4%	0.3%
3073	2.7%	1.4%	0.3%

Obviously, the best possible measurement is desirable. It should be within current capabilities to make this measurement with a maximum uncertainty of $\Delta R = .005$. Thus the maximum uncertainty in the spectral radiance at $\lambda = 250$ nm due to uncertainty in the temperature will be about 1.4%. To this must be added the uncertainty in the transmission of the window at $\lambda = 250$ nm which should not exceed 0.5%.

Another source of error is the pyrometer used to measure the blackbody temperature. To estimate the possible size of this error, we will again use equation (5). Let it be assumed that a photoelectric pyrometer of such quality as to merit the best possible accuracy statement on the NBS Report of Calibration will be used. Then the temperature uncertainties given in Table VIII in terms of standard derivation are believed to reflect the highest accuracies now attainable outside a primary standards laboratory. Table VIII shows the spectral radiance uncertainties at $\lambda = 250$ nm from this source.

Table VIII

T (in $^\circ$K)	ΔT (std. dev.) (in $^\circ$K)	$\frac{\Delta N_\lambda}{N_\lambda}$ x 100 (at $\lambda = 250$nm)
3273	5. (est.)	2.7%
3073	4.	2.4%

A further source of error in using the 3000°C blackbody would be temperature instability. Some possible sources of temperature instability might be line voltage variations into the power supply, changes in room ambient conditions, aging of the cavity, and so forth. Since the effects of these factors depend so heavily on the design of the entire blackbody system and upon the techniques employed for using the blackbody, no good estimate of error can be made in advance. It should be recognized, however, that at 3000°C and $\lambda = 250$ nm each 2 degree change in temperature is about a 1% change in spectral radiance.

To summarize then, the spectral radiance at $\lambda = 250$ nm of a 3000°C blackbody will have a minimum uncertainty of about ±5%. The maximum uncertainty will depend heavily upon the technical competence of the manufacturer of the unit and the care taken with the design. It will also depend upon the skill of the users.

For comparison the tungsten ribbon filament standard lamp is reported by NBS to have an uncertainty of also about 5% at $\lambda = 250$ nm[15]. This figure, however, requires that the NBS temperature scale be accepted as correct. If the unit is to be realized in terms of the International Practical Temperature Scale, then the maximum uncertainty in the spectral radiance of this lamp at $\lambda = 250$ nm would become ±8%[16]. Since the accuracy stated for the blackbody referred to the IPTS, then the 8% figure must be used for consistency in this analysis.

In using the standard lamp, additional error may be introduced by not setting or maintaining the lamp current accurately enough. At $\lambda = 250^{\circ}$ nm, an error of about 0.1% in current will cause about a 1% error in spectral radiance. It should be possible to hold the current to within ±.05% of the rated value. Thus, an additional uncertainty of about ±.5% will be added.

The step-up of the unit from the NBS 35 ampere standard lamp to a similar lamp operated at, say, 45 amperes should be relatively straightforward. It seems likely that this step-up could be accomplished without adding more than ±1% uncertainty.

Table IX shows a breakdown of the errors associated with a 3000°C blackbody and with a 45 ampere tungsten lamp. It also shows the sum of the errors for each, and the rms error for each. These figures should correspond roughly to the maximum and minimum uncertainties respectively.

Table IX

3000°C Blackbody		45 Ampere Tungsten Lamp	
Source of Uncertainty	Uncertainty	Source of Uncertainty	Uncertainty
Emissivity	0.5%	Optical Pyrometer (16)	4%
Window Transmission		Meter Readout (16)	1%
at Pyrometer wave-length	1.4%	Electronics (16)	1%
Window Transmission		Miscellaneous (16)	2%
at λ = 250 nm	0.5%	Current	0.5%
Pyrometer	2.7%	Scaling	1%
Sum of Uncertainties	5.1%	Sum of Uncertainties	9.5%
Rms Uncertainty	3.1%	Rms Uncertainty	4.8%

The question may be raised if there is any likelihood that the accuracy of the NBS standard lamp will be improved in the near future. According to NBS there will probably not be a new determination of the unit of spectral radiance until basic improvement is made in the realization of the temperature scale[15], since uncertainty in the temperature scale is now the largest single source of error in the unit of spectral radiance.

CONCLUSION

The 3000°C blackbody can provide a spectral radiance in the ultraviolet region between two and three orders of magnitude greater than that provided by the NBS standard of spectral radiance.

If the blackbody is very carefully and conservatively designed and if the best available pyrometer is used, it should be possible to realize the unit of spectral radiance with an uncertainty of only about one half of that associated with the tungsten standard lamp.

The 3000°C blackbody does not eliminate the need for scaling in the measurement of the spectral radiance of a high intensity arc. In the measurement of the spectral radiance of even relatively low-powered arc lamps the need for scaling is reduced by less than one half. A minimum of about three orders of magnitude will still separate blackbody and arc lamp.

The $3000^{\circ}C$ blackbody has one unique advantage. It would provide the capability to extend measurements to wavelengths less than 250 nm.

APPENDIX A

Derivation of formula for the true temperature of a blackbody having a window over its aperture.

From Planck's Law we can write

$$N_{\lambda_{T_T}} = C_1 \lambda^{-5} [e^{C_2/\lambda T_T} - 1]^{-1} , \tag{1}$$

where T_T is the true temperature of the blackbody and $N_{\lambda_{T_T}}$ is the spectral radiance of a blackbody at a temperature T_T. If the blackbody window has a transmission R_λ, we can write

$$N_{\lambda_{T_A}} = R_\lambda N_{\lambda_{T_T}} , \tag{2}$$

where $$N_{\lambda_{T_A}} = C_1 \lambda^{-5} [e^{C_2/\lambda T_A} - 1]^{-1} \tag{3}$$

Substituting equations (1) and (3) in equation (2) we have

$$R_\lambda \, [e^{C_2/\lambda T_A} - 1] = [e^{C_2/\lambda T_T} - 1] \tag{4}$$

For our purposes, $e^{C_2/\lambda T} >> 1$

Therefore

$$R_\lambda e^{C_2/\lambda T_A} = e^{C_2/\lambda T_T} \tag{5}$$

or

$$R_\lambda = e^{C_2/\lambda \left[\frac{1}{T_T} - \frac{1}{T_A} \right]} , \tag{6}$$

and

$$\ln R_\lambda = \frac{C_2}{\lambda} \left[\frac{1}{T_T} - \frac{1}{T_A} \right] . \tag{7}$$

Solving for T_T, we have

$$T_T = \frac{T_A}{1 + \frac{T_A \lambda}{C^2} \ln R_\lambda}$$

APPENDIX B

Derivation of Equation (5) relating temperature error to error in spectral radiance.

Let us partially differentiate Plank's radiation law with respect to temperature.

$$N_\lambda = C_1\lambda^{-5}\,[e^{C_2/\lambda T} - 1]^{-1} \tag{1}$$

$$\frac{\partial N_\lambda}{\partial T} = \frac{C_1C_2}{T^2\lambda^6}\,\frac{e^{C_2/\lambda T}}{[e^{C_2/\lambda T}-1]^2}$$

Let us write this as

$$\Delta N_\lambda = \frac{C_1C_2}{T^2\lambda^6}\,\frac{e^{C_2/\lambda T}}{[e^{C_2/\lambda T}-1]^2}\,\Delta T, \tag{2}$$

where ΔN_λ is the uncertainty in N_λ, and ΔT is the uncertainty in temperature.

Dividing equation (2) by equation (1),

$$\frac{\Delta N_\lambda}{N_\lambda} = \frac{C_2\Delta T}{\lambda T^2}\,\left[\frac{e^{C_2/\lambda T}}{e^{C_2/\lambda R}-1}\right] \tag{3}$$

For most cases, $e^{C_2/\lambda T} >> 1$,

so

$$\frac{\Delta N_\lambda}{N_\lambda} = \frac{C_2\Delta T}{\lambda T^2}$$

or

$$\%\text{ uncertainty in } N_\lambda = \frac{10^2\, C_2\, \Delta T}{\lambda T^2}\ . \tag{4}$$

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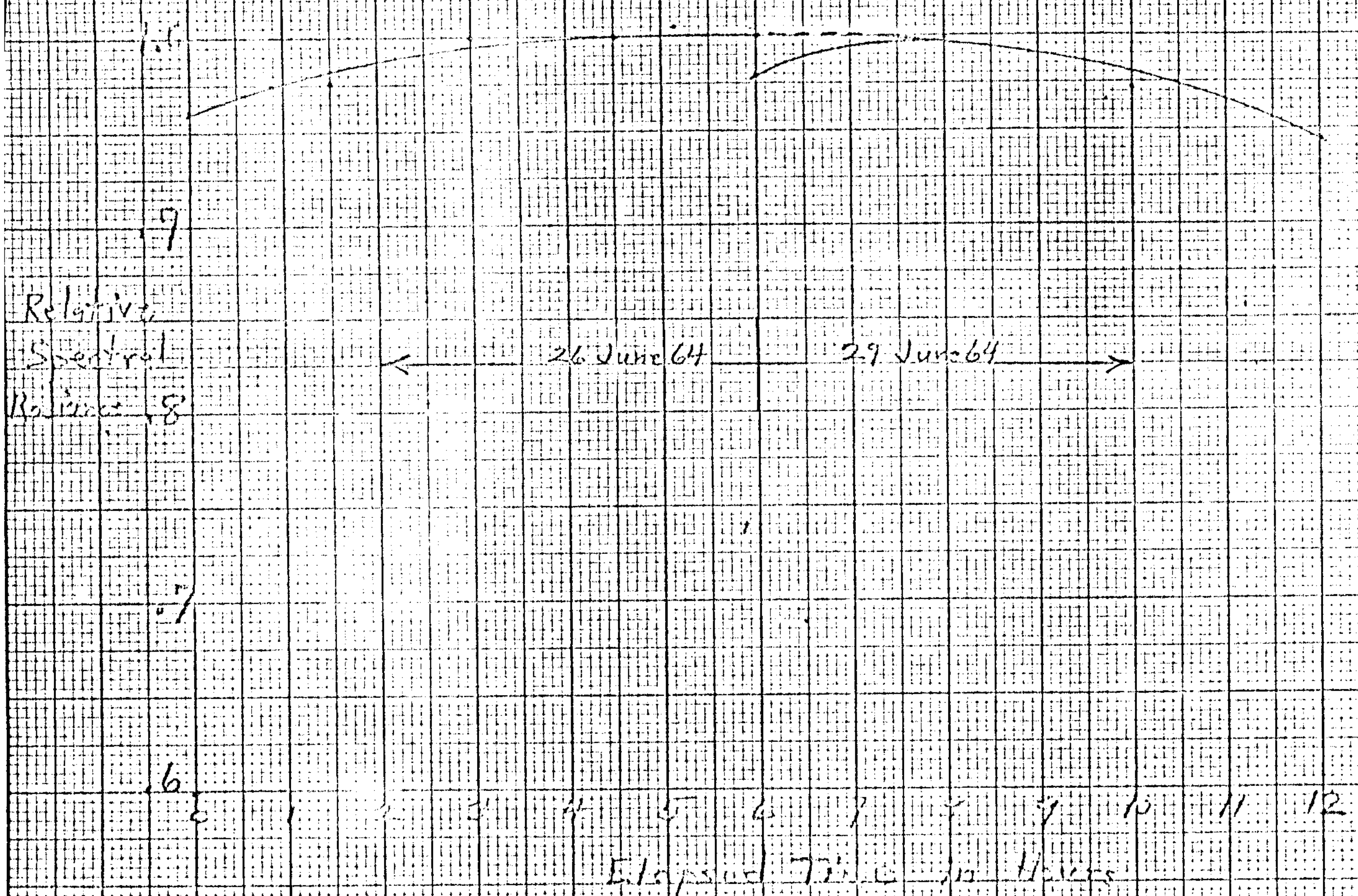
Figure I

Spectral Radiance Stability of Tungsten Ribbon Filament Lamp

Lamp Current: 50 amperes

Wavelength: 250 nm



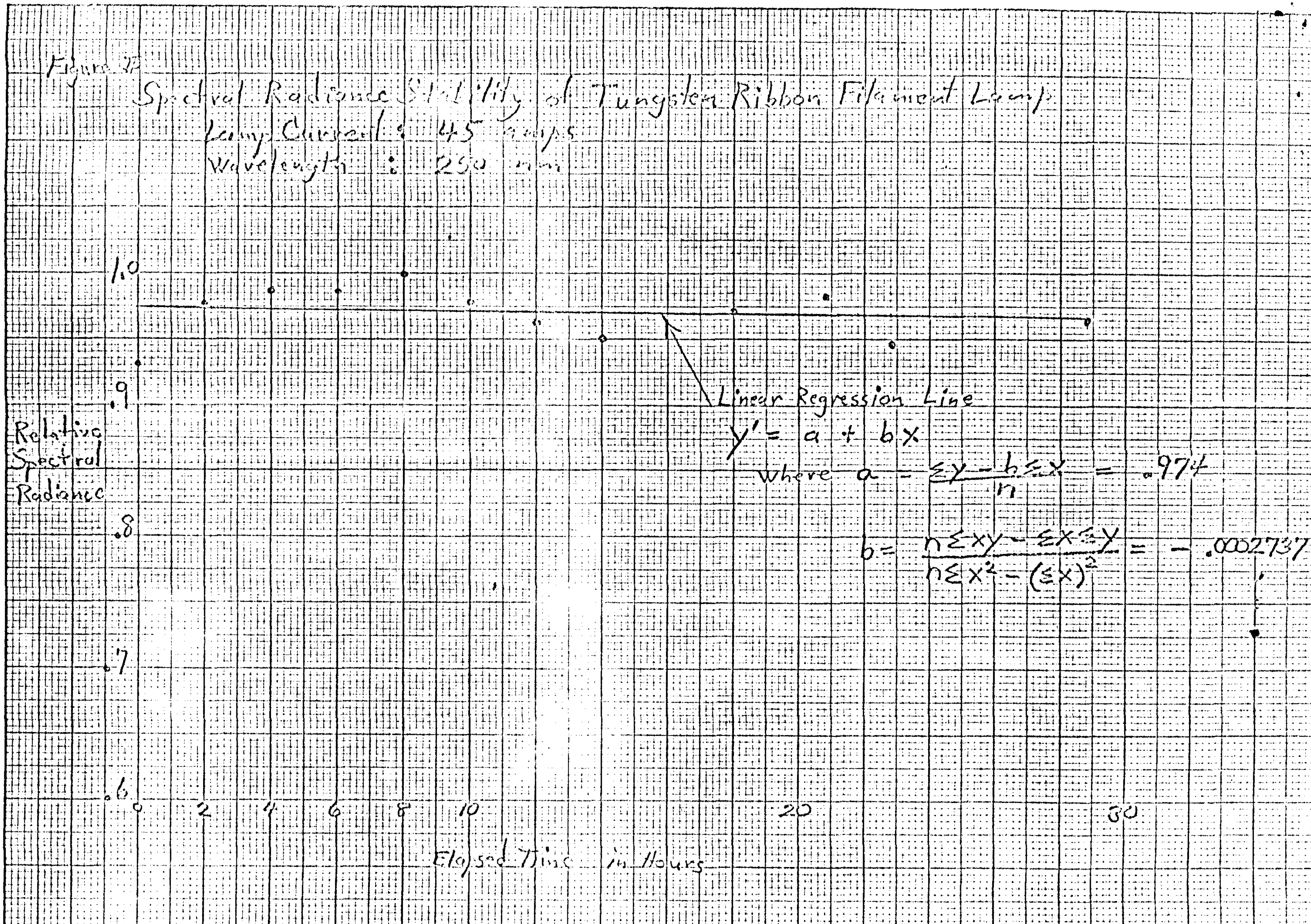


Figure
Spectral Radiance Stability of Tungsten Ribbon Filament Lamp
Lamp Current : 45 amps
Wavelength : 250 nm
Relative Spectral Radiance
1.0
.9
.8
.7
.6
0
2
4
6
8
10
20
30
Elapsed Time in Hours
Linear Regression Line
$y' = a + bx$
where $a = \frac{\Sigma y - b\Sigma x}{n} = .974$
$b = \frac{n\Sigma xy - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2} = -.0002737$